

Disappearance of the metal-like behavior in GaAs two-dimensional holes below 30 mK

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The zero-field temperature-dependence of the resistivity of two-dimensional holes are observed to exhibit two qualitatively different characteristics for a fixed carrier density for which only the metallic behavior of the so-called metal-insulator transition is anticipated. As T is lowered from 150 mK to 0.5 mK, the sign of the derivative of the resistivity with respect to T changes from being positive to negative when the temperature is lowered below ~ 30 mK and the resistivity continuously rises with cooling down to 0.5 mK, suggesting a crossover from being metal-like to insulator-like.

Charges in an electronic system are subjected to the influences of the disordered environment and interaction among themselves. Early study on the effects of disorder, ignoring interaction, revealed that a conducting system undergoes a qualitative change into an insulator when disorder is sufficiently large [1]. On the other hand, the effects due to interaction, e.g. Wigner Crystallization, turn out to be more complicated than expected [2, 3, 4, 5, 6, 7, 8]. The interplay of disorder and interaction, one of the most important and fascinating subjects in condensed matter physics, remains to be further explored.

In two-dimensional (2D) systems, despite the theoretical prediction of an insulating ground state (even the disorder is minimal) [2, 9], experimental discovery of the metal-to-insulator transition (MIT) [10] at finite temperatures (T) has stimulated further interest of investigating the interaction effects as the primary cause of MIT. Theoretical models include scattering of charges by the potential created by all other charges and impurities, and, recently, scaling theory in a multi-valley system [11]. If there is a true metallic ground state, it would be a strong indication that there exists a Quantum Phase Transition (QPT) [12, 13, 14, 15]. Whether or not the observed finite- T metal-like behavior necessarily indicates a metallic ground state is thus at the heart of the question.

Even though the metal-like phenomenon has been demonstrated in various high quality 2D systems in the T -dependence of the resistivity ρ at temperatures as low as ~ 30 mK, there lacks evidence, due to the experimental limitations, on whether the metallic signature $d\rho/dT > 0$ will survive at even lower temperatures [16]. A desired experiment would require the following two factors at the same time: a 2D sample with very high quality; and the ability of cooling 2D charges down to mK level. Performing mK-level T -dependence measurements has proven a great challenge because it demands effective cooling and noise filtering, and, moreover, a mK-level thermometry for the 2D carriers which is not yet established. An important progress in techniques of cooling 2D charges is achieved previously by Xia *et al* [17] who have demonstrated the cooling of 2D electrons down to 4 mK. Now,

on the sample side, the GaAs HIGFET adopted in recent experiments [18, 19, 20, 21] has shown exceptional quality due to the fact that there is no intentional doping in the system, thus a record-low concentration of $6 \times 10^8 \text{ cm}^{-2}$ has been achieved. Novel non-activated behaviors [19] and direct evidence of interaction effects [20] have been recently reported by using such HIGFET devices.

The present work combines both the exceptionally-clean HIGFET device with the unique cooling techniques. In a similar nuclear demagnetization refrigerator as that in Ref. [17], we have performed transport measurements on high quality 2D holes at ultra-low temperatures with a minimum bath T of 0.4 mK. The hole-density is varied by a metal gate from ~ 5 to $8 \times 10^9 \text{ cm}^{-2}$ for which the usual metal-like behavior is anticipated. Remarkably, following the metal-like behavior ($d\rho/dT > 0$) at $T > 30$ mK, a rising of ρ with cooling is observed at T below 30 mK, signifying a crossover into an insulator-like regime ($d\rho/dT < 0$). The increase of the resistivity with cooling persists down to the lowest bath T of 0.5 mK.

The sample preparation process and measurement details can be found in ref. [19]. Fig. 1 is an illustration of the cooling strategies inside the fridge. The sample sits inside a cell, filled with liquid ^3He , mounted on a silver base which is connected to the nuclear stage. Inside the cell, electrodes on the sample are first connected to short gold wires through silver paste (black dots on the sample). The gold wires are then attached to the sintered silver powder pillars each of which has one M^2 surface area. These pillars not only provide much more efficient heat exchange with the bath, but also serve as filters against the microwave noises. T is measured by a ^3He melting curve thermometer (MCT) located on the same silver base as the ^3He sample cell (not shown).

Before getting into details of the lowest- T data, a comparison is first drawn with the previous results (Ref. [19, 20]) obtained at $T \geq 30$ mK. Fig. 2 shows the T -dependence of the resistivity $\rho(T)$ for various 2D-hole densities ($p = 5.2$ to $12 \times 10^9 \text{ cm}^{-2}$) from five different samples, including sample No.7 which will be the focus. Starting from the inset, $\rho(T)$ from sample No.8

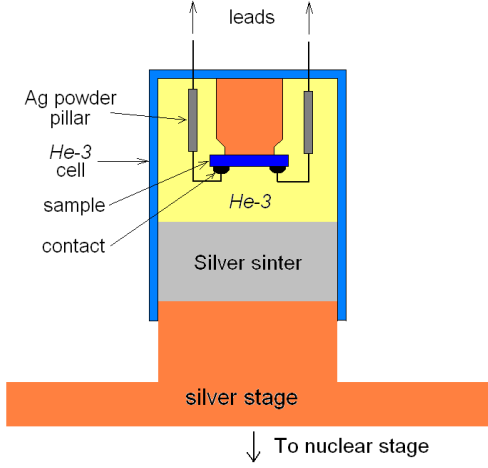


FIG. 1: (color online) Schematics of the cooling arrangements. The sample sits in a liquid ^3He cell (located on a silver base) which is connect to the mixing chamber through a copper band. The wires are connected to the sample contacts through some silver power pillars that are inside the cell.

is shown for a temperature range from 0.04 to 10 K. The rising of $\rho(T)$ with increasing T at $T > 1.5$ K (estimated Fermi temperature $T_F \sim 1.5$ K) is due to the dominating electron-phonon interaction so the system is classical. As T is lowered below 1.5 K, the system undergoes a classical-quantum crossover into the quantum regime where ρ first rises with cooling in an approximate logarithmic fashion. This behavior is confirmed in the

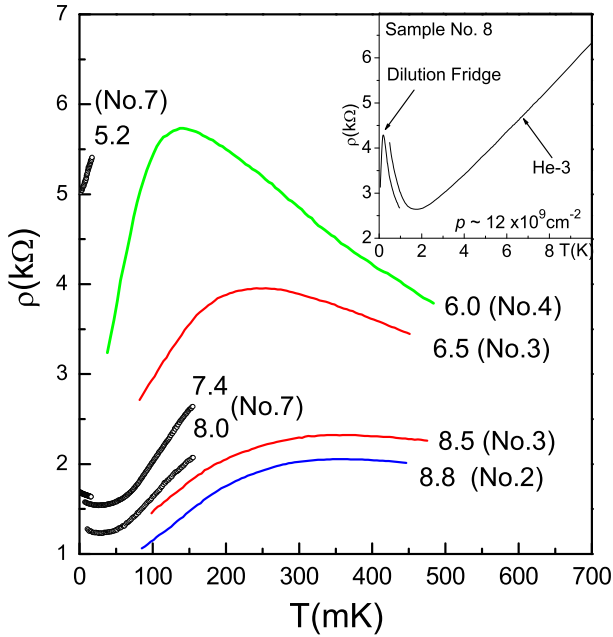


FIG. 2: (color online) Zero-field T -dependence of $\rho(T)$ from five different samples (No.2, 3, 4, 7, and 8) for densities from $p = 5.2$ to $8.8 \times 10^9 \text{ cm}^{-2}$. Inset: $\rho(T)$ from sample No.8 for $p = 10 \times 10^9 \text{ cm}^{-2}$ at $0.03 \text{ K} \leq T \leq 10 \text{ K}$.

dilution-fridge data (for a slightly different density) in the overlapped temperature range (0.5 K to 1 K). As for lower T , $\rho(T)$ exhibits the characteristic metal-like downward bending starting from the peak around 250 mK. Now, Fig. 2 provides a more detailed view of $\rho(T)$ at temperatures below 500 mK for various labeled densities measured in different samples. For samples No.2, 3, and 4, as p is lowered, the metallic bending gets stronger and the resistivity peak moves towards lower T . For sample No.7, $\rho(T)$ for $p = 7.4$ and $8.0 \times 10^9 \text{ cm}^{-2}$ agrees well with these results in the overlapped temperature region (up to 160 mK). However, the lower- T results, which we discuss for the rest of the paper, are qualitatively different from being metal-like.

Fig. 3 shows the T -dependence of $\rho(T)$ of sample No.7 from 8 mK to 150 mK for a 2D-hole density $p = 8.0 \times 10^9 \text{ cm}^{-2}$. At $T > 65$ mK, $\rho(T)$ shows the usual metal-like ($d\rho/dT > 0$) behavior. However, when T is lowered below 65 mK, $\rho(T)$ shows weaker T -dependence with cooling and reaches a minimum ($d\rho/dT = 0$). As T is further reduced, $\rho(T)$ starts to rise, faster with cooling, all the way down to 8 mK, so that the sign of $d\rho/dT$ becomes negative. The inset is a blow-up of the low- T $\rho(T)$ showing the minimum at $T_m = 32$ mK. $\rho(T)$ rises from $\sim 1.22 \text{ k}\Omega$ to $\sim 1.28 \text{ k}\Omega$ from 32 mK to 9 mK. The measurements were repeated several times with different set of leads and different current drives (I_{drive}) from 0.5 nA to 1 nA, which correspond to a change of power from 0.25 and $1 \times 10^{-15} \text{ W}$. Notice that the linear response window for $p = 5.2 \times 10^9 \text{ cm}^{-2}$, shown later in the inset of fig. 5, is $\pm 30 \text{ nA}$. For $p = 8.0 \times 10^9 \text{ cm}^{-2}$, this window

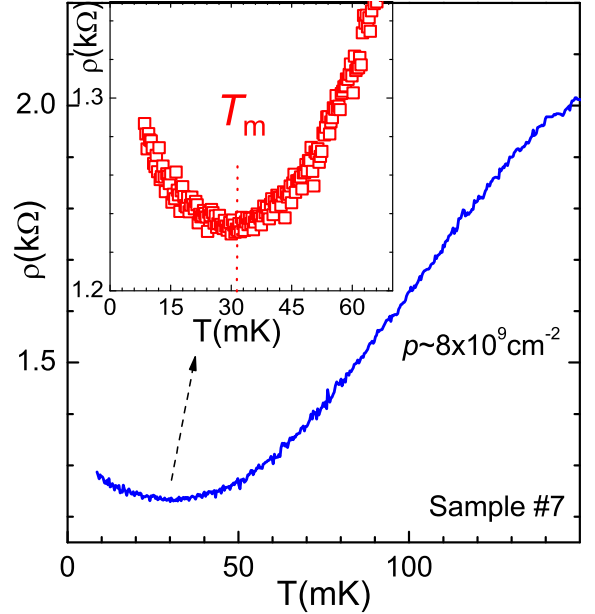


FIG. 3: (color online) Zero-field T -dependence $\rho(T)$ for $p = 8 \times 10^9 \text{ cm}^{-2}$ ($r_s \sim 33$) at a temperature range from 150 mK to 8 mK. Inset: Zoom-in of the $\rho(T)$ at low T with a minimum around 32 mK (dotted line).

is much wider so our current drives, ≤ 1 nA, are by far smaller. The results remain consistent with variation of the drives, indicating the Joule heating is negligible.

Fig. 4 is the T -dependence data for $p = 7.4 \times 10^9 \text{ cm}^{-2}$ with the T -range set from 0.5 mK to 60 mK for a closer look. The scattered data points (from 8 mK to 60 mK) are collected before demagnetization. Solid line (from 0.4 mK to 16 mK) is obtained after demagnetization for a slightly different density. $\rho(T)$ exhibits similar behavior as that for $p = 8 \times 10^9 \text{ cm}^{-2}$ except that the minimum appears at a lower T_m of 25 mK. Now, at $T \leq 25$ mK, $\rho(T)$ rises with cooling consistently down to the minimum bath temperature of ~ 0.5 mK. The increase rate of ρ versus decreasing T ($\sim 60 \Omega/16$ mK), slightly larger at $T \lesssim 6$ mK, is very similar to that for $p = 8.0 \times 10^9 \text{ cm}^{-2}$ shown in Fig. 2. The inset shows the conductivity- $\ln T$ relation which is different than the logarithmic corrections predicted for both the weak-localization and the weak interaction scenarios. The dash line, fitted for $5 \text{ mK} \leq T \leq 15 \text{ mK}$, follows the logarithmic function:

$$\sigma(T) = \sigma_0 + \frac{Ce^2}{\pi^2 \hbar} \ln(T/T_0) \quad (1)$$

with $\sigma_0 \sim 10e^2/h$, $T_0 \sim 10^{-6}$ mK, and $C \sim 4.2$ which are quite different than previous findings [23, 24]. Here, we stress on two factors: First, the interaction is not weak. With r_s approximately 35 (assuming an effective mass

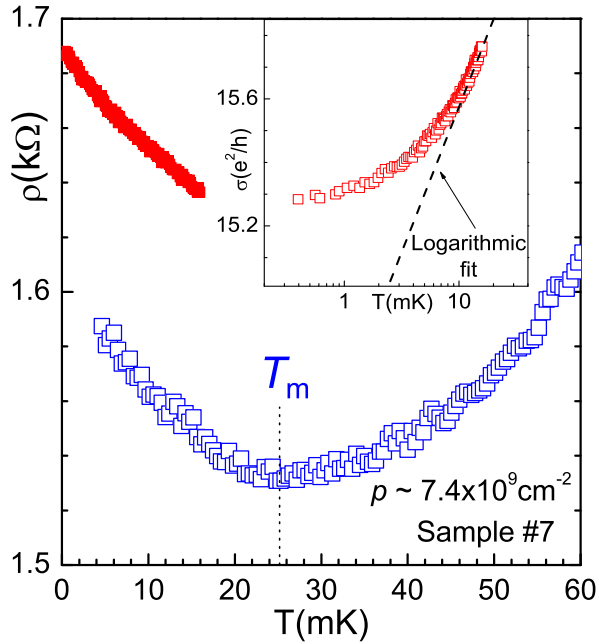


FIG. 4: (color online) T -dependence of $\rho(T)$ for $p = 7.4 \times 10^9 \text{ cm}^{-2}$ from 0.5 mK to 60 mK. Data before demagnetization (scattered points) corresponds to a slight different density than that after demagnetization due to the turning on/off the gate voltage. $T_m \sim 25$ mK (dotted line). Inset: conductivity ($\sigma = 1/\rho$) plotted versus $\ln T$ with logarithmic fit (solid line) performed for $10 \text{ mK} \lesssim T \lesssim 20 \text{ mK}$.

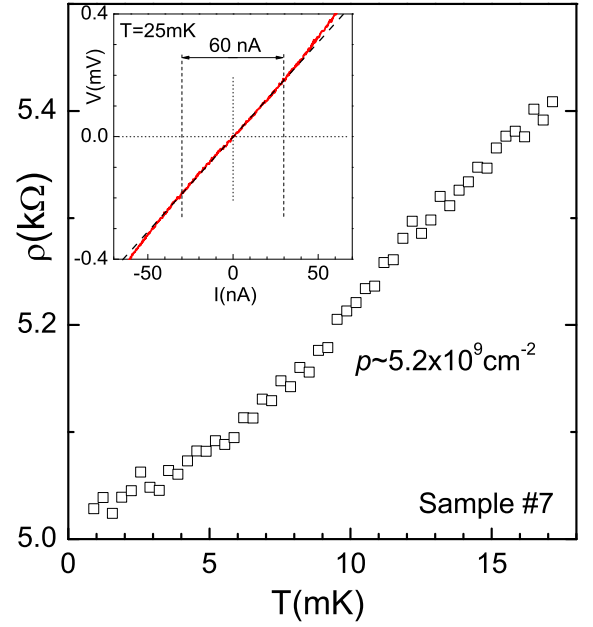


FIG. 5: (color online) T -dependence of the resistivity ($\rho(T)$) for $p = 8 \times 10^9 \text{ cm}^{-2}$. Inset: the dc-IV result at 25 mK showing a linear response window from -30 nA to 30 nA.

of $0.35m_0$), the interaction-induced modification to $\rho(T)$ could be qualitatively different than perturbations [8, 14]. The second factor, perhaps more important from the experimental point of view, is related to the possible heating effects (discussed later).

In fig. 5, the T -dependence is shown for $p = 5.2 \times 10^9 \text{ cm}^{-2}$ which already approaches the critical density ($\sim 4 \times 10^9 \text{ cm}^{-2}$) of MIT found in such devices. Comparing with the results for $p = 8.0$ and $7.4 \times 10^9 \text{ cm}^{-2}$, $\rho(T)$ for this density remains decreasing with T consistently down to 5 mK, and then shows weaker variation at lower T and tends to saturate around the base temperature of 0.5 mK. No upturning occurred. The rate at which $\rho(T)$ decreases, $\sim 0.3 \text{ k}\Omega/10 \text{ mK}$, is approximately 3 times faster than that for $p = 8.0 \times 10^9 \text{ cm}^{-2}$. The dc I-V result obtained at 25 mK is shown as the inset with the slope corresponding to a resistivity of $\sim 5.7 \text{ k}\Omega$.

Should the increase of $\rho(T)$ with cooling observed for $p = 8.0$ and $7.4 \times 10^9 \text{ cm}^{-2}$ indicate a possible insulating ground state? In order to rigorously establish an insulator, ρ should grow towards infinity as T approaches zero. Though our results show the right sign of an insulator ($d\rho/dT < 0$), $\rho(T)$ tends to approach finite values towards $T = 0$. This is very likely due to the heating effects that cause $T_{2D}(T)$ of 2D holes) lag T_{bath} , and the difference between the two may grow as T_{bath} approaches the base. Since the phonon modes are severely suppressed, the heat generated in the 2D system is carried out primarily through charge diffusion across the contacts. The cooling of the contact pads is limited by the Kapitza resistance $\sim T^{-1}$ (between the ^3He atoms and the gold con-

tacts and wires) which becomes significant at \sim mK level, producing temperature discontinuity across the boundaries. Another possible factor is there could be other processes that can exchange energy with the 2D holes. For example, the hyperfine interactions can limit the temperature since the interaction energy $g^* \mu_B B_{nu} \sim 0.1$ mK to ~ 1.4 mK (μ_B is the spin of a carrier and B_{nu} is the effective field due to nuclei). Also, there are indications of possible spin order occurring as the charge density approaches the critical density of MIT [22], which, in turn, polarize the nuclei spins. All these factors can interfere with the T -dependence measurement and the knowledge of the actual T_{2D} demands more sophisticated thermometry of the 2D holes at mK level which is beyond the scope of this paper. Despite the uncertainty related to the thermometry, the consistent increase of ρ with cooling at low- T indicates that the 2D holes are definitely being cooled even when the bath reaches its minimum T .

We point out that the increase of the resistance at low- T probably has a different origin than that resulted from weak-localization (WL) contribution [24] observed for much higher densities. The T_m in Ref. [24] appears at 300 mK which is one order higher. Moreover, our results, contrary to Ref. [24], show decrease of T_m with reducing p , which possibly indicates a different quantum effect. Also, the values of ρ in our case is much smaller: i.e. for $p = 8.0 \times 10^9 \text{ cm}^{-2}$, $\rho \sim 1.2k\Omega \sim 0.05h/e^2$ which is ~ 6 times smaller than that for a 6 times higher p in Ref. [24]. This transition from being metal-like to being insulating at $T \lesssim 25$ mK can not be explained by the existing Fermi-Liquid-based models [3, 5, 7, 8] (e.g. for a fixed density, the T -dependence of scattering by charges and impurities only leads to monotonically reduced resistivity with cooling in the metal-like regime ($d\rho/dT > 0$) [7, 8]). Notice that the estimated T_F (~ 600 mK) is significantly higher than our temperature range. Also, the scaling theory including the valleys of Ref. [11] leads to, in the diffusive limit ($k_B T \ll \hbar/\tau$, $\tau \sim$ diffusing time), a quantum critical point (QCP) that separates the two phases, and the crossing from one phase to the other requires change of interaction for fixed disorder. Here, our results, though also into the diffusive regime since $T \ll \hbar/\tau \sim 100$ mK, are from a single-valley-system.

For $p = 5.2 \times 10^9 \text{ cm}^{-2}$, the steeper metal-like decrease of $\rho(T)$ moves towards lower T , which seems in agreement with the statement made in Ref. [7] due to the reduced E_F . Since the electron-electron interaction is now much stronger ($r_s \sim 50$), the many-body coherence length l_ϕ is much reduced so that T_m could be lower than T_{2D} . The slight T -dependence for $T_{bath} \leq 3$ mK probably indicates that $\rho(T)$ eventually rises at lower temperatures when l_ϕ becomes sufficiently large, consistent with earlier results.

To summarize, for a fixed carrier density around $8 \times 10^9 \text{ cm}^{-2}$, we have observed a crossover from the metal-like state ($d\rho/dT > 0$) into an insulator-like state when T is lowered below 30 mK, and this insulator-like

behavior ($d\rho/dT < 0$) prevails down to a base temperature of 0.5 mK. These results suggest that the metal-like behavior of MIT is likely to be a finite-temperature effect and the ground state is possibly insulating.

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